**Progress report for the 3rd year of CPPA project "Tropical influences on recent and historical droughts over North America"**

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## Overview of third year's achievements

Extending the work performed in the first two years, we have focused on the analysis of the mechanisms for droughts in the third year of this project. Using a moist "aquaplanet" model, we have performed a set of simulations with specified tropical and global sea surface temperature anomalies to determine the response in the hydrological cycle in the midlatitudes. Our latest efforts include the simulations under both equinoctial and non-equinoctial conditions. The latter allows us to look into the seasonal dependence of the hydrological response. From the aquaplanet model simulations, we demonstrated that midlatitude drying can happen even with a globally uniform increase in the sea surface temperature, because a uniform increase in the SST has a latitudinally non-uniform effect on the convective heating. The largest increase in precipitation or convective heating is found to occur in the tropics. This forces an expansion of the Hadley cell, pushing the tropical and subtropical circulation systems poleward. The poleward shift of the subtropical descent and extratropical storm tracks causes subtropical drying and high latitude moistening. This provides a plausible pathway for the tropical influences on the droughts in the southern North American continent.

Continuing our efforts in GCM simulations in year 1 and 2, we have extended many of the "repeated seasonal cycle (SCYC) runs" from 20 to 50 years to ensure the statistical significance of the results. Most of the conclusions that we obtained with the 20-year runs are shown to be robust. We have also extended our analysis to the combined influences of the tropical Pacific+Atlantic SST forcing on North American droughts. The combination of a cold tropical Pacific and a warm tropical North Atlantic is found to be conducive to the formation of droughts in the U.S.

We have also looked into the future of North American droughts by analyzing the IPCC AR4 simulations for the 21st century. A strong downward trend in the precipitation minus evaporation (P-E) over the southwest U.S. is found in the majority of the IPCC model simulations. The projected change in P-E is large enough that we expect to detect a substantial increase in the intensity and duration of droughts in the southwest within a few decades. This result is reported in Seager et al. (2007).

## Aquaplanet model simulation of midlatitude drying

The aquaplanet model was constructed from an atmospheric GCM (NCAR CCM3.10) with full physics. Figure 1 shows the simulated zonal mean precipitation rate from a "control run" (black), forced with an imposed idealized zonally symmetric SST with a maximum on the equator, and a "warming run" (red) that differs from the control run only by a constant increase of 4°C everywhere in the imposed SST. Both are run under a perpetual equinoctial condition. The uniform surface warming is enough to produce a concentrated increase in the tropical convective activity, leading to an expansion of the Hadley Cell (not shown). The expanded Hadley Cell implies a poleward shift of the subtropical descent (the climatological dry zone), thereby drying in the 25°N-35°N band. This zonally symmetric picture is similar to that simulated by climate models for the 21st century with double $CO_2$ and may also contribute in part to the North American drought of 1998-2002, during which the effect of greenhouse gas forcing has begun to emerge.

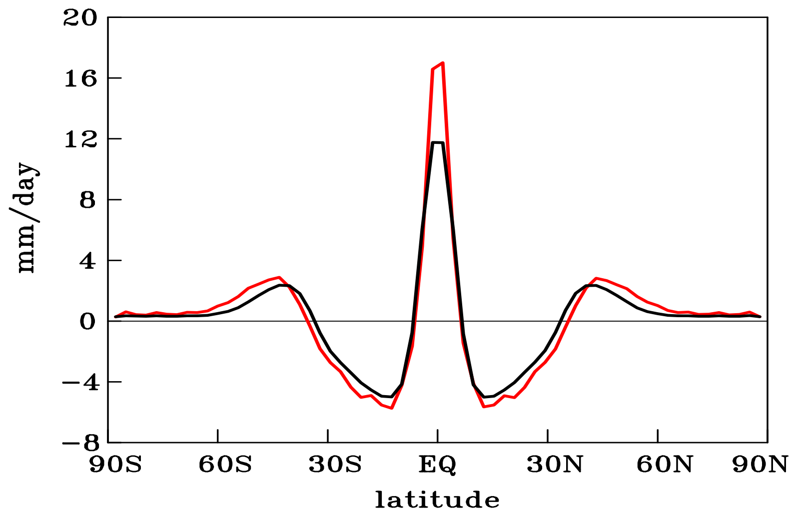


*Fig. 1 The zonal mean precipitation rate, in mm/day, simulated by the Control Run (black) and +4°C Warming Run (red). Both use a moist aquaplanet model forced with a zonally symmetric SST with a maximum on the equator. A uniform 4°C increase is added to the SST for the Warming Run. The Warming Run exhibits a poleward shift of the precipitation pattern in the subtropics and midlatitude, corresponding to drying in the 25°N-35°N band.*

The nature of the subtropical drying in the +4C warming run is further analyzed in terms of the moisture budget. The poleward shift in the circulation pattern is found to be important in changing the hydrological balance in the subtropics and midlatitude. Figure 2a shows the climatological mean of the zonal-mean relative humidity (RH) from the control run and Fig. 2b the difference between the +4C and control runs. The effect of the surface warming is a poleward expansion and shift of the subtropical dry zone (areas with light color in mid-troposphere in Fig. 2a). As a result, at 30°N and 30°S, just poleward of the climatological minimum of RH in the control run, we found a decrease in RH in the +4C run. This is physically consistent with the suppressed rainfall in the same latitude bands.

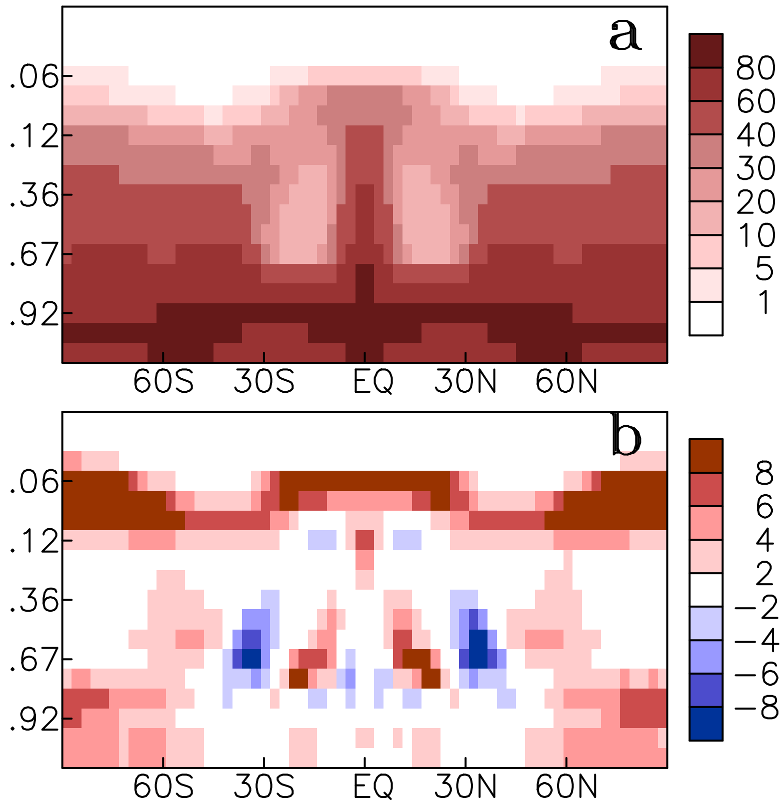


*Fig. 2 (a) The climatological mean and zonal mean of the relative humidity from the control run using the aquaplanet model. (b) The difference between the +4C warming run and control run. The scale at left indicates the sigma level ($\sigma$ = 1 is the surface; $\sigma$ = 0.1 is approximately the tropopause). The unit is % with color scale shown at right.*

**Climate change and the future of North American droughts**

We have also analyzed the potential changes in the duration and intensity of North American droughts in the future climate by analyzing the IPCC AR4 simulations for the 21st century. The precipitation minus evaporation (P-E) averaged over the southwest U.S. is found to decrease in the majority of the IPCC model simulations. The trend in P-E is large enough that we expect to detect a substantial increase in the intensity and duration of droughts in the southwest U. S. within a few decades. The change in precipitation due to the changes in the location and intensity of transient eddies is found to be important for producing the drying trend in the model. See Seager et al. (2007) for further detail.

**Contributions of local SST anomalies to the 1998-2002 drought**

Continuing our efforts of GCM simulations in year 1 and 2, we have extended many of the 20-yr simulations to 50 years to reaffirm the statistical significance of the results. We have also added extended "repeated seasonal cycle" runs forced with only the tropical Indian Ocean SST anomaly for the 1998-2002 climate epoch. We found a strongly zonally symmetric response to the isolated Indian Ocean SST anomaly, with a ridge over the tropics and a pair of troughs in the subtropics and midlatitude, which are not conducive to the generation of the observed North American drought from 1998-2002. This solidified our previous speculation that a stand-alone Indian Ocean SST anomaly is not sufficient in producing North American drought, that the "cold Eastern Pacific + warm Western Pacific" components are more important.

**Multi-basin influences**

As described in "Outlook and emerging issues" in our yr-2 report, we recognized that while the Indo-Pacific SST anomalies are of first order importance, the SST anomalies over the Atlantic could also play a role in regulating North American droughts. This point has been investigated more closely during the 3rd year. Both statistical analyses for the observation and a set of new GCM runs with imposed tropical Atlantic SST anomalies indicate that a warm tropical North Atlantic tends to help the development of drought over the U.S. Combined with our previous results, the combination of a cold tropical Eastern Pacific, a warm Western Pacific, and a warm tropical North Atlantic form an ideal SST pattern for North American drought. Since the Pacific and Atlantic SST anomalies are not independent of each other, we have used an atmospheric GCM with a partial coupling to a mixed layer ocean over the Atlantic to assess their interaction. It is found that the in the majority of ENSO events, the tropical North Atlantic SST (TNA) anomaly in boreal spring is controlled primarily by the Pacific ENSO forcing but exceptions - about one in five cases - exist when the evolution of TNA is determined by internal variability. This information can be used to attribute the predictability in the precipitation anomalies over North America to the SST anomalies in different basins. This multi-basin analysis for the SST-drought connection is ongoing and will be improved with more in-depth analyses of GCM runs with imposed multi-basin SST anomalies.

**Highlights of yr-3 accomplishments**

• Obtained new insights into the process of midlatitude drying caused by an enhanced tropical convective activity and the poleward expansion of Hadley Cell. This process is likely relevant to the turn-of-the century (1998-2002) and future North American droughts when global SST warms up.

• Solidified the conclusion that a warm tropical Indian Ocean SST anomaly alone is insufficient in producing North American droughts.

• Uncovered a projected drying trend over the southwest U.S. in the 21st century from multiple IPCC climate model simulations. This trend is strong enough to imply a detectable increase in the intensity and duration of droughts over the southwest U.S. within a few decades.

• Quantified the combined influences of the tropical Pacific and tropical Atlantic SST anomalies on the precipitation anomalies over the United States. The combination of a cold tropical Pacific and a warm tropical North Atlantic is found to be ideal for producing droughts over the United States.

**Plan for the extended period**

We have requested an extension of the time period of this project with no additional cost. In accordance with the expiration date of our NOAA-CICAR joint institute, we have requested the extension of the expiration date of this project to June 30, 2008. The following are the justification and the planned activities for the extended period.

The first three years of this project has progressed as we have envisioned. However, our GCM and idealized model simulations have produced a large amount of valuable data that even exceeded our initial expectation. As such, we believe it is useful to spend more time to further explore the model outputs and use the added analyses to further consolidate and enrich our conclusions. The major activities for the extended period of our study will be to more thoroughly synthesize the results from the GCM and idealized model simulations, especially those with the multi-basin SST forcing, and to finish writing up the results for publication. The efforts devoted to this project over the extended period will be approximately evenly divided into the analysis and synthesis of the model results, and the writing of more papers to disseminate our final results.

**Publications**

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, and N. Naik, 2007: Model projections of an imminent transition to a more arid climate in southwestern North America, *Science*, **316**, 1181-1184

Huang, H.-P., A. W. Robertson, Y. Kushnir, and S. Peng, 2008: Hindcasts of Atlantic SST gradient: the influences of the ENSO forcing and the Atlantic preconditioning, submitted to *J. Climate*